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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Survivability of an aircraft in combat is achieved by not getting hit, or withstanding the effect: suffered hits. To assess the latter aspect of survivability of a given military aircraft, live-fi: are performed on its wings. However, these tests may fail to provide accurate and complete vulner: assessments, because the static and quasi-static ground loading techniques they currently rely on replicate the loads encountered during flight. This effort focuses on developing a numerical simu: technology for predicting the consequences of battle damage on the flight and flutter envelopes o: fighters, assessing the impact of several contributors to aircraft survivability using full-order as reduced-order computational models, and assisting in the development of new dynamic live-fire : testing methodologies that may remedy the shortcomings of current static ground-testing technique: report itself focuses on the technical achievements made during the first nine months of the

third year of funding.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBI Charbel Farhat
a. REPORT	b. ABSTRACT	c. THIS PAGE			**19b. TELEPHONE NUMBER** *code)* (650) 723-3840

1 OBJECTIVES

1.1 Original Objectives

It was proposed to conduct a three-year research effort focused on developing, validating, and exploiting a high-fidelity and high-performance numerical simulation technology for predicting the effects of combat damage on the flight and flutter envelopes of military aircraft. To this effect, it was proposed to build on previous achievements in CFD (Computational Fluid Dynamics)-based nonlinear computational aeroelasticity funded by AFOSR (Grant F49620-99-1-0007), and perform the following research tasks:

- *Advanced modeling and computational methodologies.* It was proposed to research and develop high-fidelity and high-performance methodologies for modeling and simulating the effect of damage on the aerodynamic performance, stability, control, and aeroelastic behavior of military aircraft. These include, among others, the concept of "phantom" elements for facilitating the introduction of damage in the computational fluid and structure models, fast methods for evaluating transient effects, and the sensitivity analysis by the adjoint method of flight mechanics and flutter criteria such as lift, drag, stability derivatives, and flutter speed with respect to various damage parameters including the size and location of a hole.

- *Dynamic live-fire ground-testing methodology.* Assisted by the developed simulation technology, it was also proposed to investigate a reconfigurable wing loading methodology based either on tethers or embedded piezoelectric actuators which replicates in-flight loading conditions, and allows the structure to properly react when damaged.

- *Validation.* Finally, it was proposed to collaborate with Dr. Greg Czarnecki and his team at the Wright-Patterson Air Force Base (AFB) to validate the proposed simulation technology, and assess the feasibility of the proposed dynamic loading methodology. It was also proposed to work with Dr. Mike Love at Lockheed-Martin Aeronautics to explore how the proposed modeling and simulation technology can help in reducing some of the test costs of the JSF (Joint Strike Fighter) program.

1.2 Revised Objectives

After one year of performance on this grant, the Flight Test Center at the Edwards Air Force Base requested an additional emphasis on *aeroelastic reduced-order models* to speed-up the prediction of the flutter envelopes of modern aircraft fighters. This request was accommodated in the form of an additional task (see Research Task 8 below).

2 STATUS OF EFFORT AND ACCOMPLISHMENTS

During the third year of funding, effort focused on Research Task 6 and Research Task 8.

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FA 9550-05-1-0038

2.1 Outcome of Research Task 6: A Stress-Control-Based Live-Fire Ground Testing Methodology

LFT is supposed to be conducted as if the aircraft was in flight, and had been hit by an anti-aircraft artillery round. Typically, it is performed on a wing. The tanks are loaded with fuel, and high-velocity air is blown by a battery of jets across the wing which is loaded by computer-controlled hydraulic jacks to simulate in-flight loads. In one test, an explosive bullet is fired away from the fuel tank. In another test, it is fired inside the fuel tank. The explosive bullet generates a shock wave that travels through the fuel and imparts loads on the wing's skin and internal structure. Consequently, a portion of the wing skin deforms into the air stream then rips off. If the damaged wing remains largely intact, it is currently concluded that the limited structural damage would enable a pilot to fly the airplane home [1].

The LFT procedure outlined above has at least one main deficiency: the high-velocity air blown by the jets and the computer-controlled hydraulic jacks applied to the tip of the wing do not reproduce the in-flight loads. In particular, the hydraulic jacks introduce an unrealistic restraint at the tip of the wing whose root is already cantilevered.

To reproduce the in-flight loads, a loading methodology should reproduce the true stress state of the structure. Given a set of flight conditions, this stress state can be predicted fairly accurately by numerical aeroelastic simulation. Hence, the main idea reported here is to consider a wing, instrument it with a number of embedded actuators, and program these actuators to produce the desired aeroelastic stress state field denoted here by $\bar{s}$. Such actuators could be, in principle, piezoelectric actuators, thermal actuators, simple tethers, or any combination of these. Unlike hydraulic jacks, embedded actuators do not restrain the wing at any location, and potential tethers soften the restraints they induce because of their compliance.

Let g_i denote the gain of the i-th embedded actuator, and $\mathbf{u}_i$ denote the displacement field of a wing structure due to this actuator and its gain g_i. Under the usual linear assumption, when all N_a embedded actuators are activated, the total displacement of the wing is

$$\mathbf{u} = \sum_{i=1}^{i=N_a} \mathbf{u}_i g_i = \mathbf{U}\mathbf{g} \tag{1}$$

where $\mathbf{U}$ is the matrix of displacement fields $\mathbf{u}_i$, and $\mathbf{g}$ is the vector of gains g_i. From Eq. (1), it follows that if $\mathbf{s}_i$ denotes the stress field associated with $\mathbf{u}_i$, then the stress state of the wing structure is given by

$$\mathbf{s} = \sum_{i=1}^{i=N_a} \mathbf{s}_i g_i = \mathbf{S}\mathbf{g}$$

where $\mathbf{S}$ is the matrix of stress fields $\mathbf{s}_i$ associated with the gains g_i.

Hence, the crux of the idea reported here is to find the gain vector for which $\mathbf{s} = \bar{\mathbf{s}}$ — that is,

$$\mathbf{S}\mathbf{g} = \bar{\mathbf{s}}. \tag{2}$$

Unfortunately, Eq. (2) can be exactly satisfied only if the total number of actuators N_a is equal to the number of degrees of freedom of interest, and using such a large number of actuators is

unfeasible as well as undesirable. In particular, the component of the structure that is expected to be damaged should not be instrumented so that no actuator is destroyed and the in-flight loads are reproduced as much as possible after damage is inflicted on the instrumented structure. Hence, a residual

$$\mathbf{r} = \bar{\mathbf{s}} - \mathbf{S}\mathbf{g} \qquad (3)$$

is to be accepted but minimized. Here, the Euclidean metric is chosen for this purpose. Furthermore, it is well-known that some actuator locations are more efficient than others in prescribing a particular shape [2,3], and therefore a particular stress state. For this reason, a good strategy consists in minimizing $\|\bar{\mathbf{s}} - \mathbf{S}\mathbf{g}\|_2$ over both the locations and gains of the N_a actuators, for different values of N_a.

Alternatively, after damage is inflicted on the wing, it can be inspected and described by holes in the computational structural dynamics and computational fluid dynamics models. Then, the vector of actuator gains can be reset to the value which minimizes

$$\|\mathbf{r}\|_2 = \|\bar{\mathbf{s}}_d - \mathbf{S}\mathbf{g}\|_2, \qquad (4)$$

where $\bar{\mathbf{s}}_d$ is the stress state predicted for the damaged wing by numerical aeroelastic simulation. Once the damaged wing is loaded according to this reconfigured gain vector, its structural integrity can be assessed, and further numerical simulations can be performed to evaluate its remaining flight capability.

In summary, the stress-control-based live-fire ground testing methodology developed so-far is governed by the mathematical problem

$$\min_{\mathbf{g} \in \mathbb{R}^{N_a}} \quad \|\bar{\mathbf{s}} - \mathbf{S}\mathbf{g}\|_2 \qquad (5)$$

$$\mathbf{C}(\mathbf{g}) \leq 0, \qquad (6)$$

where $\mathbf{C}(\mathbf{g})$ is a matrix of constraints specifying, for example, that each actuated member does not exceed a certain percentage of the yield stress and that the total energy of actuation does not exceed a certain threshold. Note however that the solution of the above minimization problem is adequate for the envisioned application if and only if $\bar{\mathbf{s}} \in R(\mathbf{S})$, and that the range of $\mathbf{S}$, $R(\mathbf{S})$, depends on the number, location, and type of the actuators.

Let $\mathbf{S}_a$ denote the matrix of stress fields s_i associated with the gains g_i when *all* members of the test structure are actuated. If $\bar{\mathbf{s}} \notin R(\mathbf{S}_a)$, this "range check" indicates that, using the chosen type of actuators, the test article cannot be put in the aeroelastic stress state $\bar{\mathbf{s}}$ even if each one of its members is instrumented. In this case, the range check also suggests that additional internal members and/or external members such as tethers are needed to control the stress sate of the test article. Then, if additional members are introduced in the structure for controlling its stress state, stiffness-and-mass checks must then be performed *a posteriori* to ensure that the few additional members have not significantly changed the characteristics of the structure — for example, its eigen modes.

Advances in the methodology outlined above including the use of one-dimensional versus bender actuators, its accuracy, feasibility (no member yielding, minimum and practical energy requirement), and demonstration for the ARW2 wing have been reported in 2004 in the AIAA paper [7]

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and documented in the attached comprehensive Ph. D. report entitled "A Stress-Control-Based Live-Fire Ground Testing ". Essentially, it was found that at least for the ARW2 wing, tethers are almost always required to reproduce the in-flight loads with sufficient accuracy.

In order to check whether the above result is primarily due to the fact that the ARW2 wing has a large aspect ratio, the proposed loading methodology was next assessed for *delta*-like wings. The smaller aspect ratio of such wings tends to make their structures statically indeterminate, which in turn tends to improve the performance of self-equilibrated one-dimensional actuators. More specifically, two such wings were considered: a high-speed civil transport wing and an F-16 wing in clean configuration. In both cases and for several damage scenarios, it was also found that external tethers cannot be avoided if in-flight loads are to be reproduced accurately. More specifically, it was found that the entire objective of the loading methodology can be achieved using only a few tethers. For example, it was found that for the F-16 wing, eight well-positioned tethers can reproduce in most cases the in-flight stress states of the wing with a global relative error of the order of 10%. On the other hand, it was also found that the current usage of computer-controlled hydraulic jacks at the tip of a wing to simulate in-flight loads typically results in relative errors that exceed the 50% level.

2.2 Outcome of Research Task 8: Reduced-Order Modeling for Near-Real-Time Flutter

In order to enable real-time flutter analysis, a computational methodology based on adaptive reduced-order modeling (ROM) was developed. In this methodology, the structure is represented by a truncated modal set, the fluid by a reduced-order basis obtained by Proper Orthogonal Decomposition (POD) for a given Mach number, and the resulting basis is adapted for variations in the Mach number by interpolation of the subspace angles. This computational technology was implemented in AERO and applied to a complete F-16 fighter configuration. Good correlations between full-order simulation results, reduced-order simulation results, and flight test data, were obtained and documented in an AIAA paper that appeared in 2005.

References

[1] Czarnecki G. Wright-Patterson Air Force Base, private communication.

[2] Partch R and Farhat C. Energy reduction methods for static shape control of space truss structures, Proceedings Sixth International Conference on Adaptive Structures, Key West, Florida, November 13-15, 1995.

[3] Partch R and Farhat C. Energy vs. accuracy vs. number of actuators trade-off studies for the shape control of space truss structures, AIAA Paper 96-1285, 37th Structural Dynamics Meeting, Salt Lake City, Utah, April 15-17, 1996.

3 PERSONNEL SUPPORTED

During the third year of funding, this research grant supported the Principal Investigator, Charbel Farhat, a research associate, Steve Jones, a post-doctoral assistant, Thuan Lieu, two graduate students, Charbel Bou-Mosleh and Arthur Rallu, two visiting faculty during summer, Michel Lesoinne and Bruno Koobus, and a project assistant, Margarita Duenas.

4 PUBLICATIONS

1. C. Farhat, J. Cortial, C. Dastillung and H. Bavestrello, "Time-Parallel Implicit Integrators for the Near-Real-Time Prediction of Linear Structural Dynamic Responses," *Internat. J. Numer. Meths. Engrg., (in press)*

2. C. Farhat, "CFD on Moving Grids: From Theory to Realistic Flutter, Maneuvering, and Multidisciplinary Optimization," *Internat. J. CFD, (in press)*

3. T. Lieu, C. Farhat and M. Lesoinne, "Reduced-Order Fluid/Structure Modeling of a Complete Aircraft Configuration," *Comput. Meths. Appl. Mech. Engrg., (in press)*

4. C. Farhat, A. Rajasekharan and B. Koobus, "A Dynamic Variational Multiscale Method for Large Eddy Simulations on Unstructured Meshes," *Comput. Meths. Appl. Mech. Engrg., (in press)*

5. C. Farhat, G. van der Zee and P. Geuzaine, "Provably Second-Order Time-Accurate Loosely-Coupled Solution Algorithms for Transient Nonlinear Computational Aeroelasticity," *Comput. Meths. Appl. Mech. Engrg.*, Vol. 195, pp. 1973-2001 (2006)

5 INTERACTIONS/TRANSITIONS

5.1 Conferences

1. T. Lieu and C. Farhat, "Adaptation of POD-based Aeroelastic ROMs for Varying Mach Number and Angle of Attack: Application to a Complete F-16 Configuration," *AIAA Paper 2005-7666, U.S. Air Force T&E Days*, Nashville, Tennessee, December 6-8 (2005)

2. C. Farhat, J. Cortial, H. Bavestrello and C. Dastillung, "A Time-Decomposed Parallel Implicit Algorithm for Accelerating the Solution of Second-Order Hyperbolic Problems,", *Eighth U.S. National Congress on Computational Mechanics*, Austin, Texas, July 24-28 (2005)

3. C. Farhat and Bjarte Haegland, "On the Numerical Stability of a Class of Loosely-Coupled, Higher-Order Fluid/Structure Solution Algorithms", *Fifth International Conference on Computation of Shell and Spatial Structures*, Salzburg, Austria, June 1-4 (2005)

4. T. Lieu, C. Farhat and M. Lesoinne, "POD-based Aeroelastic Analysis of a Complete F-16 Configuration: ROM Adaptation and Demonstration," *AIAA Paper 2005-2295, 46th AIAA Structural*

Dynamics & Materials Conference, Austin, Texas, April 18-21 (2005)

5. J. Cortial and C. Farhat, "A Time-Domain-Decomposed Implicit Methodology for the Time-Parallel Solution of Second-Order Hyperbolic Problems," *Sixteenth International Conference on Domain Decomposition Methods,* New York, January 12-14 (2005)

5.2 Transitions

The second-generation nonlinear aeroelastic simulation platform AERO developed by the Principal Investigator and his research group was transitioned to the Flight Test Center at the Edwards Air Force Base (Point of Contact/User: Dr. John Sun) for application to the aeroelastic modeling and simulation of the JSF. It was also delivered to the Naval Research Laboratories (Point of Contact/User: Dr. John Michopoulos) for enabling research in the design of a dynamic data-driven system for structural health monitoring and critical event prediction.

6   PATENT DISCLOSURES

None.

7   HONORS/AWARDS

- Who's Who in Computational Science and Engineering (2005)

- Fellow of the American Society of Mechanical Engineers (2003)

- Fellow of the International Association of Computational Mechanics (2002)

- Fellow of the World Innovation Foundation (2001)

- Fellow of the US Association of Computational Mechanics (2001)

- Fellow of the American Institute of Aeronautics and Astronautics (1999)